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Abstract 15445

One of the most critical phases of a space mission occurs when the spacecraft reenters the earth's atmosphere. To insure successful return of future lunar and planetary mission spacecraft, research investigation of the physics of reentry flight must continue.

To avoid the associated radio-blackout problem and to permit the use of small severe-environment, solid-propellant vehicles for reentry research, the NASA has developed a 3-pound, 1,000-watt X-band telemetry system. This system can operate under accelerations greater than 100g and will be able to transmit high-rate data directly during the reentry blackout period from vehicles traveling at 25,000 feet/second or greater. Its small size and weight will permit use in vehicles whose payload capacity is 10 pounds or less. This paper describes that system and its use in a small Trailblazer II reentry-research payload.

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Summary

A considerable amount of research into the physics of high-velocity atmospheric flight has been conducted using small solid-propellant rocket vehicles launched from the NASA Wallops Island Facility. This research has been hampered because none of the known systems for avoiding the radio-blackout problem have been sufficiently small or rugged to be used in high-acceleration vehicles whose payload weight capacity is less than 10 pounds.

The X-band telemetry system described in this paper has been created to satisfy such requirements. It weighs 3 pounds, is small in size, can operate under accelerations greater than 100g, and will be able to transmit high-rate data directly during the reentry blackout period from vehicles traveling at 25,000 feet/second or greater.

As an example of the application of this reentry telemetry system, a Trailblazer II payload installation is described and the flight plans reviewed.

Introduction

The phenomenon of "reentry radio blackout" is well documented[1,2] and its effect painfully understood by those attempting to make and transmit research measurements during the period of high-velocity atmospheric flight.

A number of means for avoiding or minimizing the effect of reentry radio blackout have been suggested[3], although as a practical matter only two are proved and in common use.

The oldest technique is that of employing an onboard magnetic tape recorder to store the data for transmission after the vehicle emerges from the blackout region. Unfortunately, the size, weight, and environmental characteristics of available tape recorders prevent their application to small solid-propellant reentry-vehicle payloads. While ferrite-core storage systems[4] can overcome these disadvantages, they are of limited data capacity.

The other technique for avoiding blackout is the operation of the telemetry system RF link at a frequency greater than the critical frequency of the ionized air layer surrounding the reentry vehicle. The X-band telemetry system described herein operates on that principle, and is a miniaturized and improved version of the X-band telemetry system which has been successfully employed on Project RAM reentry-research vehicles[5].

Compared to storage-and-playback systems, direct-transmission reentry telemetry offers two basic advantages: it can provide data up to the occurrence of any catastrophic payload failure during the severe reentry period, and greater performance from small vehicles is generally possible since the extra margin of heat-protection material required to guarantee survival of the reentry period is not necessary.

A graphic illustration of the ability of a system operating at a frequency of X-band to provide direct telemetry for the case of a 25,000 foot/second small reentry payload is shown in figure 1. This figure also compares the relative ability of conventional VHF telemetry frequencies to cope with the reentry blackout problem.

Description of Telemetry System

This direct reentry X-band telemetry system is a 1,000-watt peak-power output time-division multiplex type, employing pulse-position modulation and having a data capacity of 900 samples per second. The combined weight of the two units which comprise the system - encoder and transmitter - is 3 pounds. Both units have been especially developed to provide a small, lightweight, and environmentally rugged system and, in that regard, represent a substantial improvement over the X-band system previously employed on Project RAM vehicles. The system, including the low level commutator, is completely solid state with the exception of the transmitter magnetron.

Encoder

The encoder unit accomplishes the functions of commutation and encoding of the sampled data to a pulse-position modulation (PPM) format for keying of the associated transmitter. A simplified block diagram of the unit is shown in figure 2.

The data input to the encoder is 20 low level differential input channels, having a full scale of about 20 millivolts. Sampling rate is 45 times per second, resulting in a total of 900 samples per second.

Some of the pertinent characteristics of the encoder unit are:

Capacity: 20 × 45 (20 channels, each sampled 45 times per second)

Input: 20 millivolts full scale, balanced

Differential input impedance: 500,000 ohms

Input impedance to ground: 50 megohms

Common mode rejection: 90 db for ±6 volts, d.c. to 1,000 cps

Linearity: ±1/4 percent from the best straight line

Scatter and jitter: 1/2 percent or less

Back current: less than 1/4 microampere

Offset: less than 0.2 percent

Output: PPM and PDM formats

Encoding: 100 microseconds for zero scale, 500 microseconds for full scale

PPM pulse output: 5-volt amplitude into 50 ohms; 3-microsecond pulse duration; 0.2-microsecond pulse rise time

Input power requirement: 28 ± 4 volts d.c.; about 100 milliamperes

Size: $2\frac{1}{4}$-inch diameter, 4 inches long

Weight: 16 ounces

In normal use, two of the encoder input channels are purposely not gated, the resulting void in the pulse train being used for frame synchronization in accordance with IRIG standards.

Transmitter

A simplified block diagram of the transmitter is shown in figure 3. This unit is designed around the recently developed MXM-16 magnetron which is capable of operation under comparatively extreme environmental conditions.

The transmitter is triggered by the train of 5-volt amplitude pulses from the encoder PPM output. Since two pulses are created for each data sample, the transmitter pulse rate is 1,800 per second, or slightly lower if data channels are ungated for frame synchronization purposes. Duration of the 1,000-watt peak-power pulse is 1 microsecond.

An unusual design feature of this transmitter is the use of a transformer-coupled charging circuit in place of the conventional charging-choke arrangement. The advantages this circuit provides, resulting in a smaller, lighter, and more efficient transmitter, are: (1) the elimination of a d.c.-d.c. converter since the charging circuit can operate directly from a 28-volt d.c. source, (2) rapid recovery time to satisfy the minimum pulse spacing requirements of high data rate PPM formats, (3) elimination of the possibility of modulator lockup since the controlling SCR is a-c coupled, and (4) elimination of a voltage regulator since the circuit is inherently self-regulating.

For this reentry-communication application, an especially desirable feature of the MXM-16 magnetron is the ability to operate without damage into high VSWR loads. Such a mismatch condition generally occurs on reentry vehicles when the highly conductive ionized layer forms in close proximity to the antenna aperture. In the past, isolators have been necessary between the antenna and the transmitter to protect magnetrons of other types.

Although the MXM-16 tube operates under high VSWR conditions, a "pulling" of the frequency does occur. Measurements of this "pulling" have been made by operating the transmitter into the slot-array antenna described in a later section of this paper, and causing a deliberate antenna mismatch. The mismatch was accomplished by covering the entire antenna aperture with a layer of metallic foil. This is believed to simulate the worst possible plasma condition, and resulted in a change in VSWR from the normal value of less than 1.5:1 to about 10:1 for the detuned case. The resulting frequency shift was less than 10 megacycles and in the lower-frequency direction. In consideration of the bandwidth and AFC circuitry of the receiving systems employed this amount of shift is not expected to be troublesome.

General performance characteristics of the transmitter are:

Frequency range: 8,800 to 9,600 megacycles

Peak-power output: 1,000 watts

Pulse characteristics: 1-microsecond duration; 0.1-microsecond rise time

Trigger requirements: 5-volt amplitude pulse

Output: coaxial output, 50-ohm impedance

Input power requirements: 24 to 30 volts d.c. at 1.07 amperes

Size: 3-inch diameter, $4\frac{1}{2}$ inches long

Weight: 28 ounces

A photograph of the encoder and transmitter units is shown in figure 4.

Environmental Characteristics

The design of both the encoder and transmitter has been based on the requirement for optimum operation during and after exposure to an environment slightly in excess of that anticipated in actual flight applications. Environmental test criterion has been:

Static acceleration: 120g

Shock acceleration: 120g, 10-millisecond pulses

Vibration: 20g RMS, 20 to 2,000 cps

Temperature: 0° to 160° F

Altitude: 10^{-4} mm Hg equivalent

Satisfactory operation at these levels has been achieved. In addition, some testing has been performed which indicates that present designs are capable of reliable operation at levels in excess of those indicated. Although the ultimate environmental limit will probably be determined by the magnetron, a further tube ruggedization effort should be able to extend that limit.

System Accuracy

An estimate of the accuracy with which this telemetry system can transmit data has been made by two means: by calculation using the known individual element inaccuracies, and by actual measurement of the overall "transfer characteristic" from encoder input to the output of the ground data readout equipment.

The mathematical accuracy determination was made by tabulating all sources of error and then applying the square root of squares probability criterion. This calculation showed that the accuracy of the recovered and readout data should be within ±1.25 percent for the condition where the carrier S/N ratio is equal to or exceeds the noise improvement threshold. For a PPM/AM system, the noise improvement threshold can be as small as 6 db[6].

The actual measurement of overall performance was made using the equipment shown in figure 5 which included all elements involved in a flight mission for the transmission, reception, recording, and final readout of the data. The accuracy determination was made by comparing the carefully measured encoder input "quantities" with the "quantities" derived from the readout of the received data. For the condition of a receiving system input signal level approximately 8 db greater than system threshold, the overall measured accuracy was about ±1 percent.

Installation in a Trailblazer II Payload

A good illustration of an application of this X-band telemeter system is a payload which will be flown on a Trailblazer II vehicle.

Figure 6 shows the general overall configuration of the payload, which is a conical shape having a relatively sharp nose, a maximum diameter of about 7 inches, and an overall length of about 30 inches. The manner in which the encoder and transmitter are installed is also shown; in addition, the antenna and battery pack components are identified.

Payload Antenna

The antenna employed on this vehicle has been developed especially to satisfy the antenna pattern requirements of the mission for the unstabilized, spinning payload. As in the case of the encoder and transmitter, minimum antenna system weight has been a goal.

Figure 7 shows a sketch of the slot-array antenna design and a photograph of the complete assembly. The antenna unit, which is used as an integral part of the payload structure, is fabricated of aluminum and weighs 14 ounces.

The antenna, as well as a major part of the payload itself, is covered with a noncharring ablative material. The antenna is recessed slightly from the skin of the vehicle so that a sufficiently thick covering of dielectric material is maintained between the antenna slots and the ablative covering to prevent changes in antenna impedance and radiation characteristics as the heat-protection covering ablates in flight.

Figure 8 shows the patterns and radiation efficiency achieved by this antenna configuration. Of particular note is the relative freedom of large fluctuations in the pattern about the spin axis. Such a pattern is necessary to assure continuous signal reception regardless of the roll orientation of the payload. Experience has shown that this pattern is difficult to achieve with other antenna configurations.

Battery System

The size and weight of the battery pack used to power this telemetry system is obviously a function of the length of the flight mission. In this particular payload, a pack of 19 HR-05 batteries is used, providing a total capacity of 15 watt-hours. Since the total power consumption of the telemeter is 33 watts, an operating time of 27 minutes is provided. In consideration of a total flight time of about 7 minutes, this battery pack provides a good flight safety margin and sufficient capacity to permit the normal brief periods of operation on internal power prior to launch.

Conventional umbilical connections to the payload are provided for warmup and other prelaunch operational checks of the telemeter on external power.

Total Onboard RF System Weight

For this particular payload, the use of the 3-pound telemetry system results in the following total onboard weight chargeable to the RF system:

Encoder and transmitter	44 ounces
Antenna	14 ounces
Battery pack	15 ounces
Total	4 pounds, 9 ounces

Trailblazer Payload Flight Plans

Vehicle System

The Trailblazer II is a unique rocket vehicle system developed by the NASA for conducting reentry physics research. It is an unguided, spin stabilized, all solid-propellant five-stage vehicle which can propel lightweight payloads to reentry velocities approaching 25,000 feet/second.

The unique feature of the Trailblazer system is the orientation of the stages with respect to each other to form the vehicle configuration. A photograph of the vehicle on the launch pad and a drawing of the configuration showing the individual stages are shown in figure 9.

The drawing shows how the third, fourth, and fifth (payload) stages are mounted under a protective shroud in an "upside-down" manner on top of the first two stages. Operation of the vehicle, which flies the trajectory shown in figure 10, is as follows: the first two stages are used to boost the velocity package on the ascending part of the trajectory; spin of the vehicle, induced by canted fins on the second-stage motor, is used to stabilize the vehicle and maintain the attitude of the velocity package through the remainder of the flight; prior to the apogee of about 200 miles the velocity package and expended second stage are separated; after apogee has been reached, the third stage is fired propelling earthward the reentry stages out of the open end of the velocity package shroud; the fourth- and fifth-stage motors are then fired in succession, driving the payload stage into the atmosphere to provide the reentry environment for the research measurements.

Figure 11 shows the relationship of reentry velocity and payload capacity for the five-stage Trailblazer II payload vehicle described; it illustrates the need for lightweight telemetry and instrumentation components. The "payload capacity" represents the load-carrying ability of the payload stage which is available for onboard research instrumentation including the weight of the telemetry system. Excluding any instrumentation, the reentry weight of the payload stage configuration of figure 6 is about 20 pounds.

Range Instrumentation

Figure 12 is a plan view showing the trajectory of the payload and the location of the three X-band receiving systems supporting the launch.

Receiving systems #1 and #3, located at Wallops Island and the NASA tracking site at Coquina Beach, North Carolina, respectively, are identical and described fully in a previous paper[7]. These stations are monopulse trackers, having an antenna beam width of about 1.2°. Since the publication of the referenced paper, provisions have been incorporated at each of these stations for the option of either linear (horizontal or vertical) or circular (right or left) polarization.

Station #2 located at Wallops Island uses a radar-slaved antenna with an effective diameter of 30 feet at X-band. This receiving system, which is operated by MIT Lincoln Laboratories, has a sensitivity advantage of approximately 13 db over stations #1 and #3.

Assistance in acquisition of the vehicle X-band signal is provided the two Wallops located stations by VHF acquisition aid antenna systems tracking a third-stage VHF telemeter signal, from radar tracking data or from precalculated trajectory information. Once the signal is acquired by station #1, it is operated in a self-tracking mode.

Acquisition assistance for the Coquina Beach X-band receiving station is available from a VHF acquisition aid system or from precalculated antenna pointing data. This station is also self-tracking once acquisition has been accomplished.

Data Playback and Reduction

The magnetic tape containing the received X-band data will be processed through an automated playback and data-reduction system which is described in reference 5. Final output of that system will be a time-history tabulation or plot of the measured quantity of each data channel.

Concluding Remarks

1. The 3-pound X-band system described will avoid reentry radio blackout making possible direct telemetry at relatively high data rates from payloads traveling at 25,000 feet/second or greater in the earth's atmosphere.

2. The weight, size, and environmental characteristics of this system will enable it to be used in payloads experiencing accelerations of over 100g and having a weight capacity of less than 10 pounds.

3. This system is expected to greatly extend the usefulness of relatively inexpensive and small solid-propellant vehicles for accomplishing reentry physics research. In the case of extremely small payloads, such as those flown using the Trailblazer vehicle, onboard reentry-period measurements have not previously been possible because of the lack of a suitable telemetry system.

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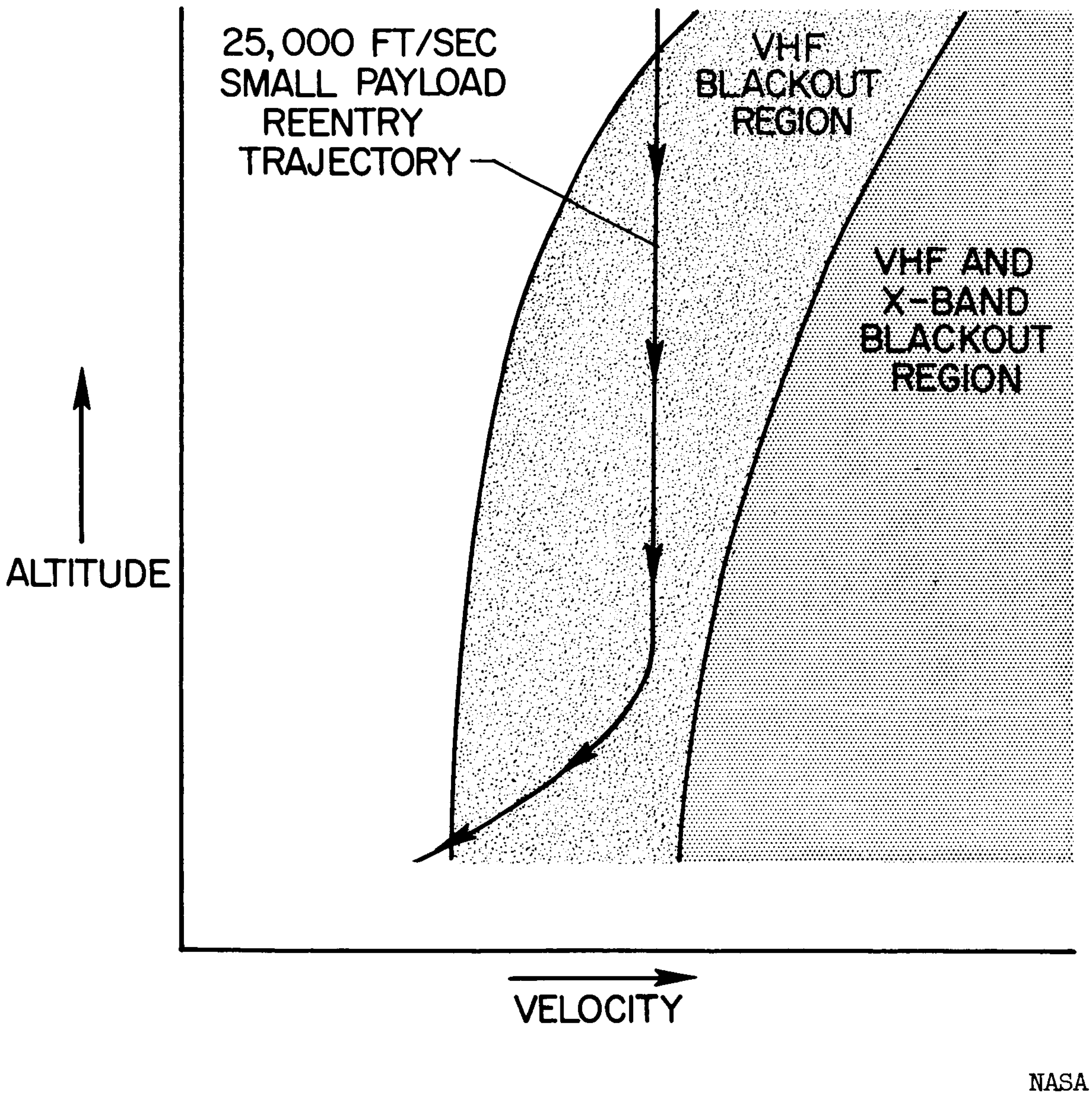

Figure 1.- Comparison of X-band and VHF reentry attenuation.

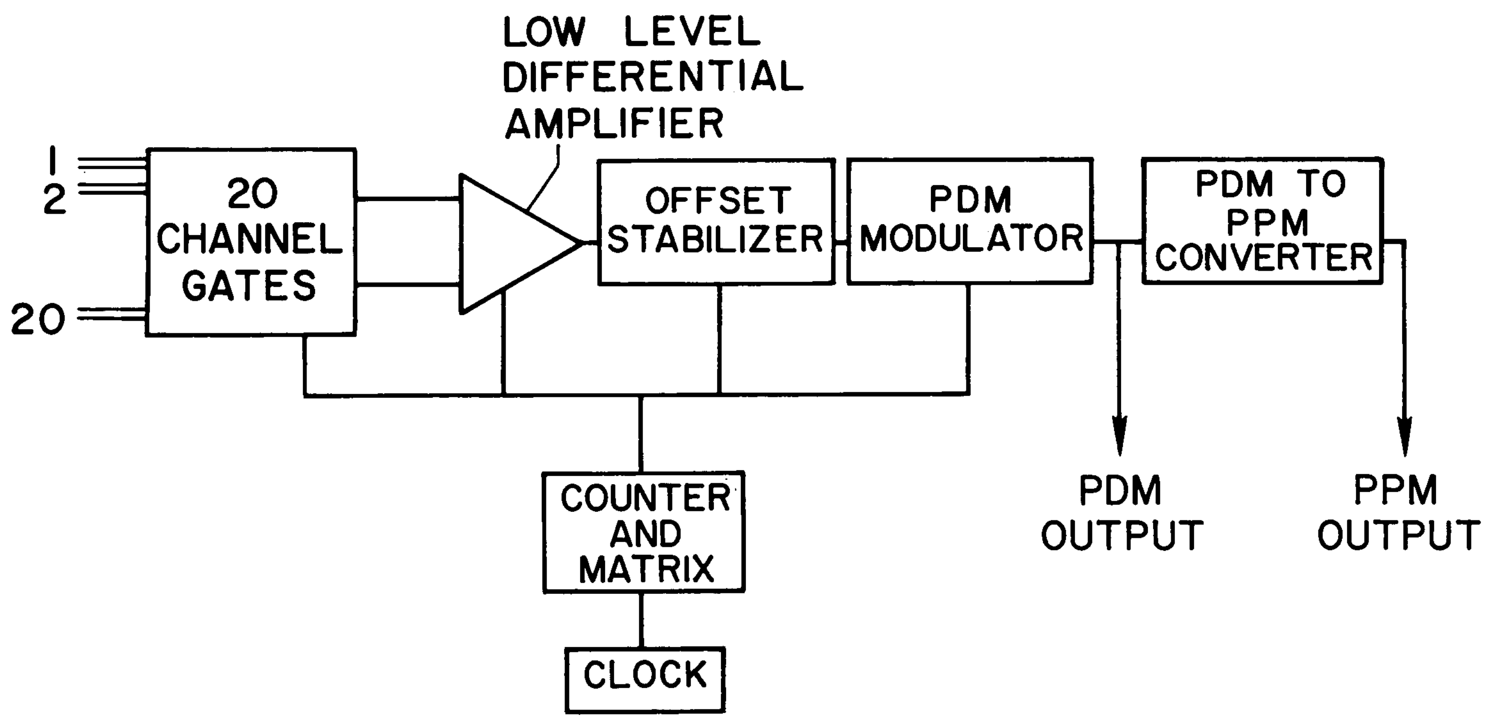

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Figure 2.- Encoder simplified block diagram.

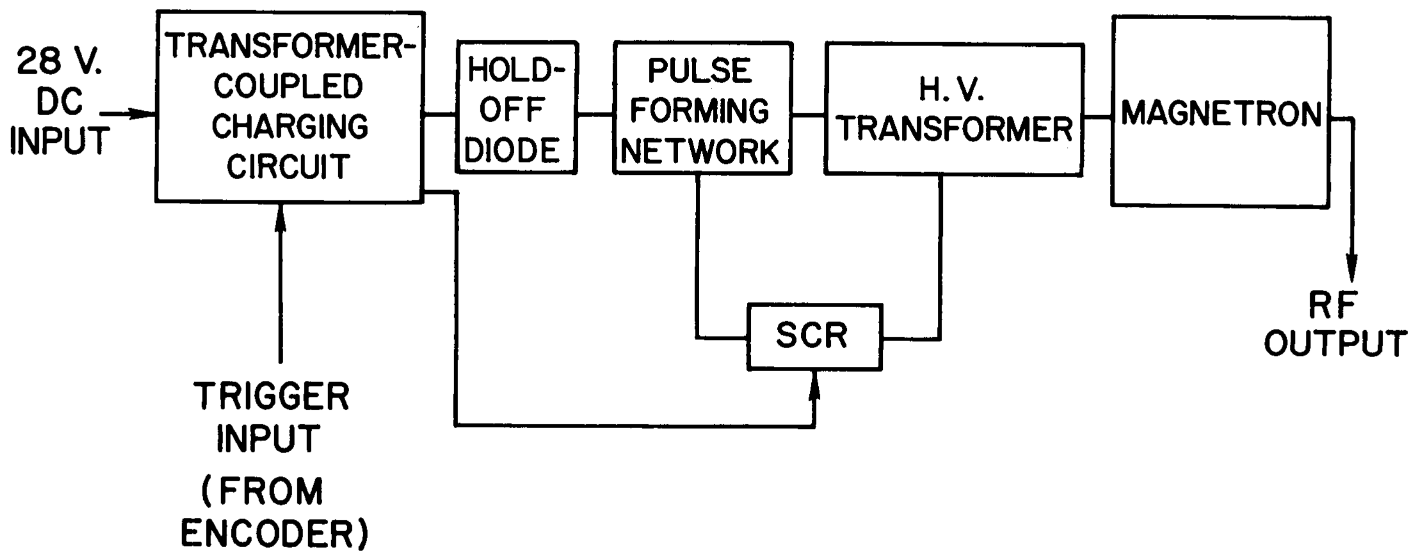

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Figure 3.- Transmitter simplified block diagram.

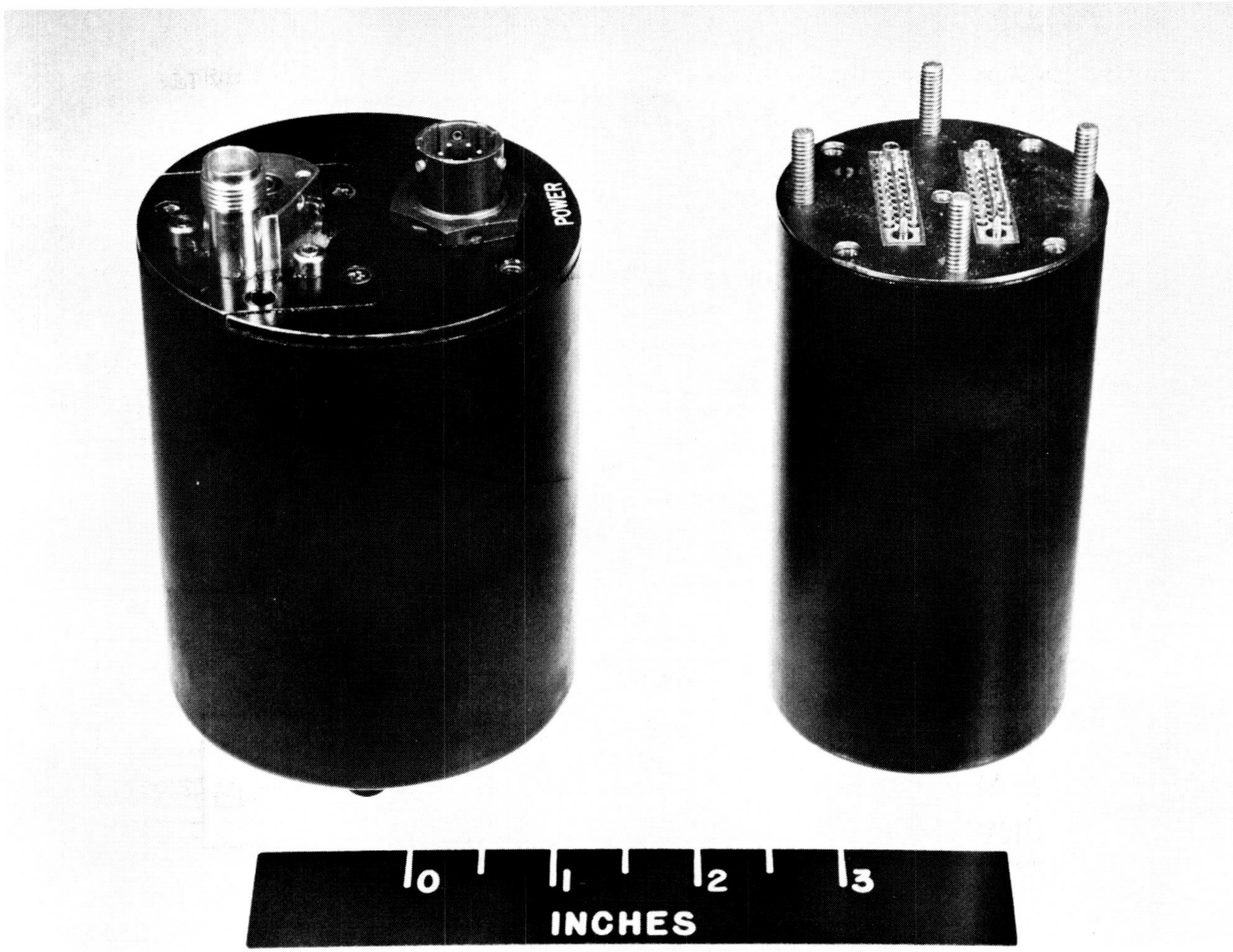

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Figure 4.- Transmitter and encoder.

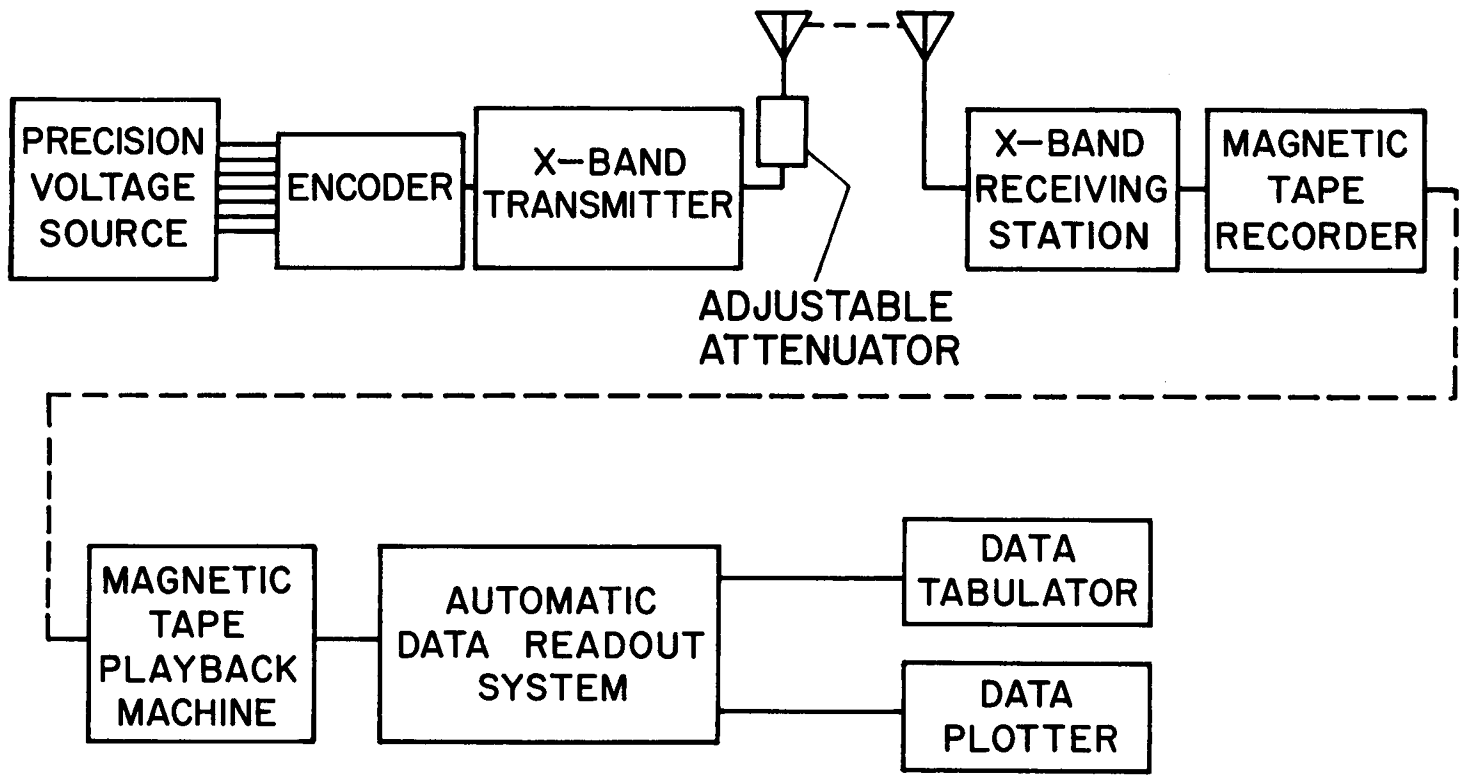

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Figure 5.- Equipment used for telemetry system accuracy evaluation.

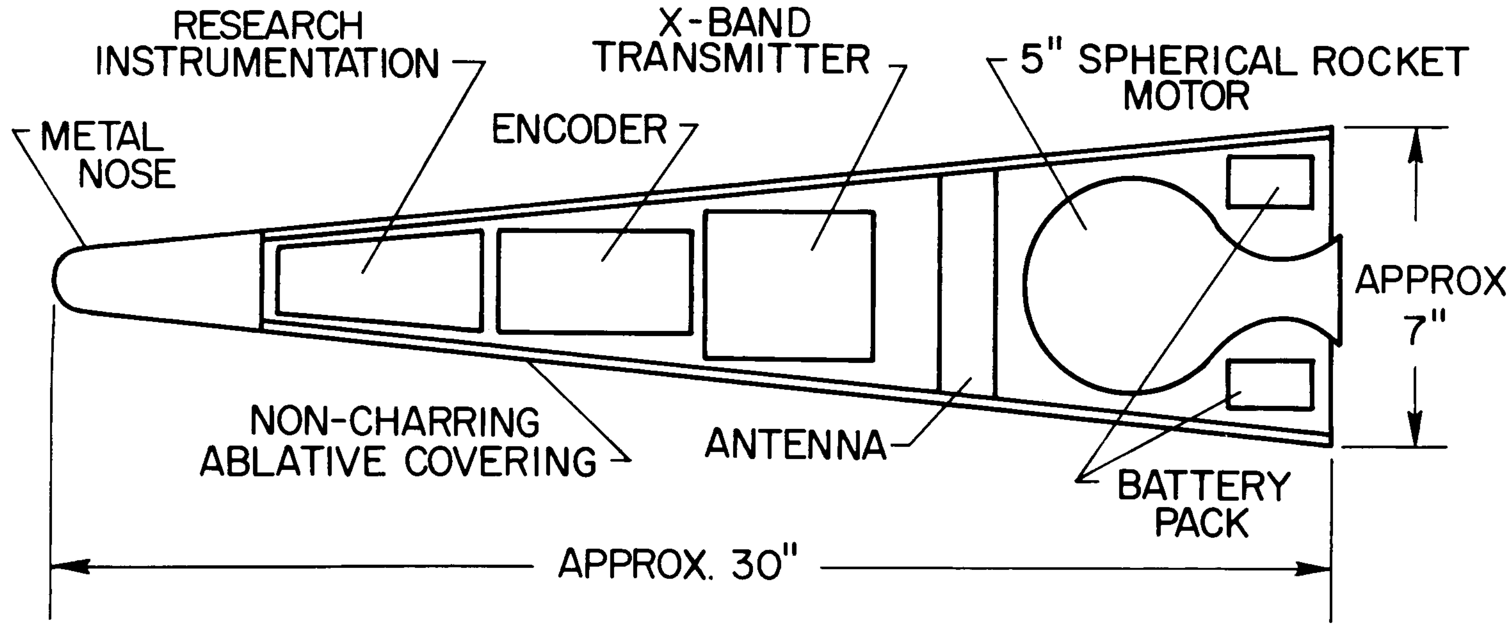

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Figure 6.- Trailblazer II payload configuration.

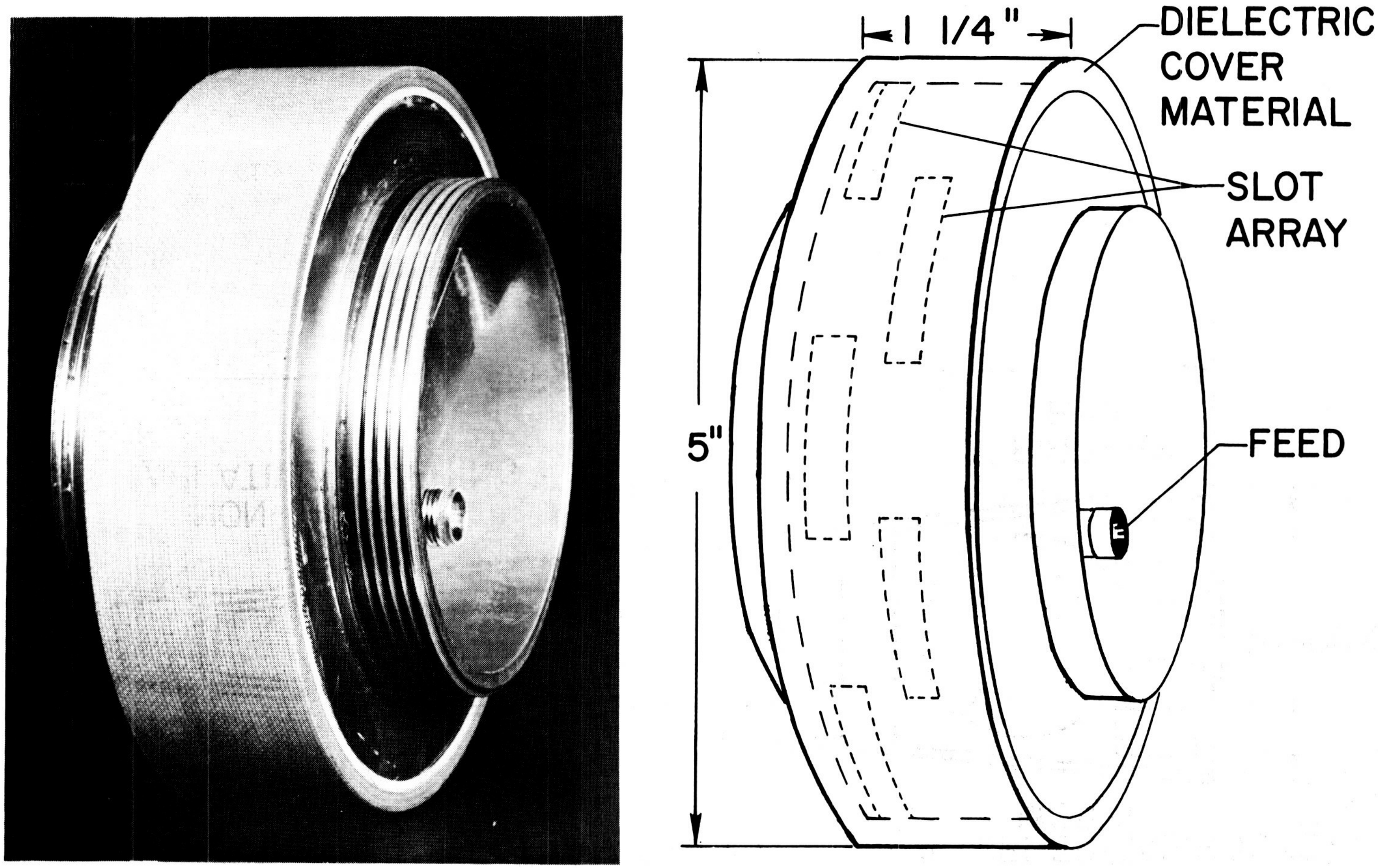

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Figure 7.- Slot array payload antenna.

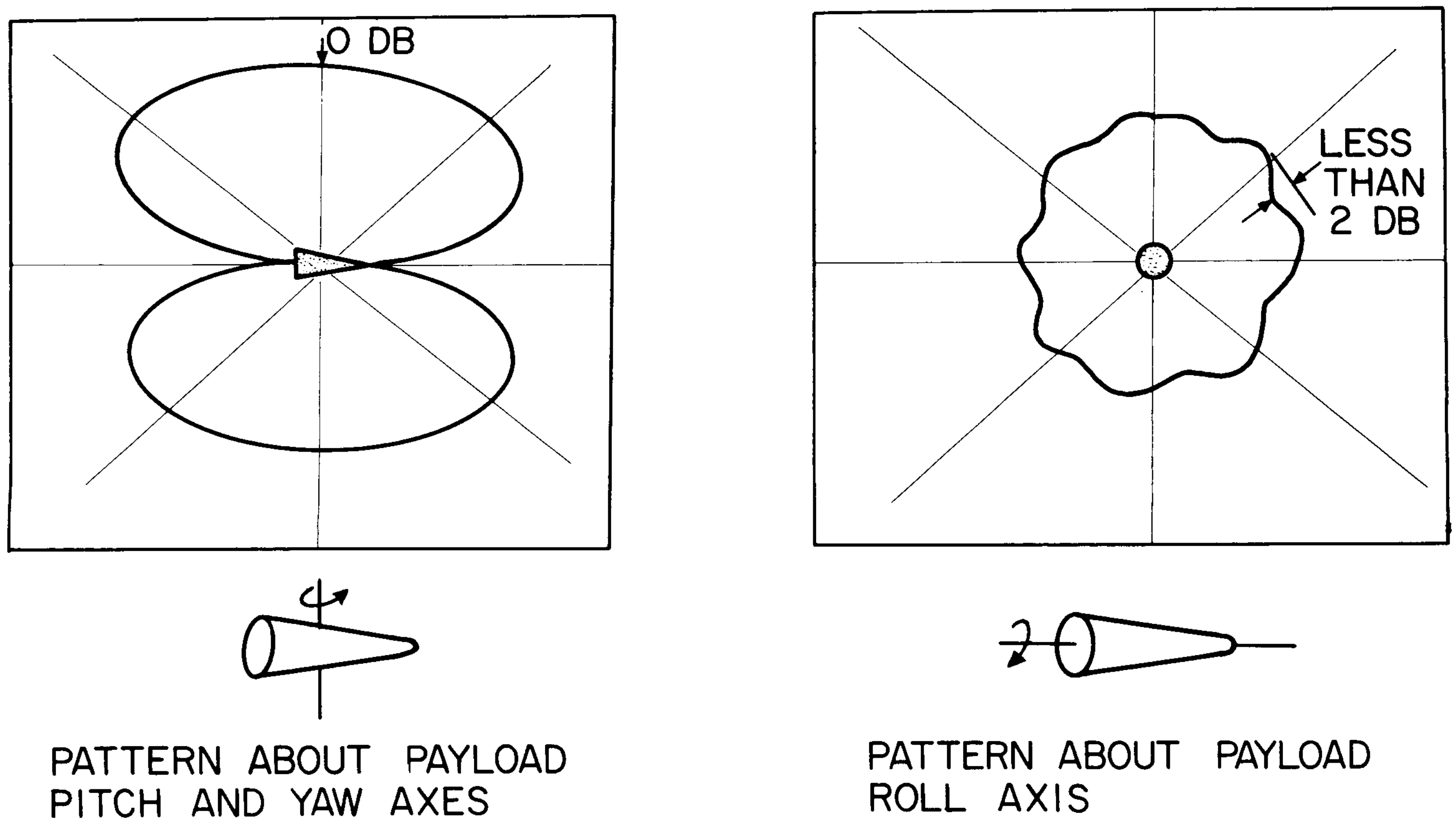

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Figure 8.- Slot array antenna radiation patterns.

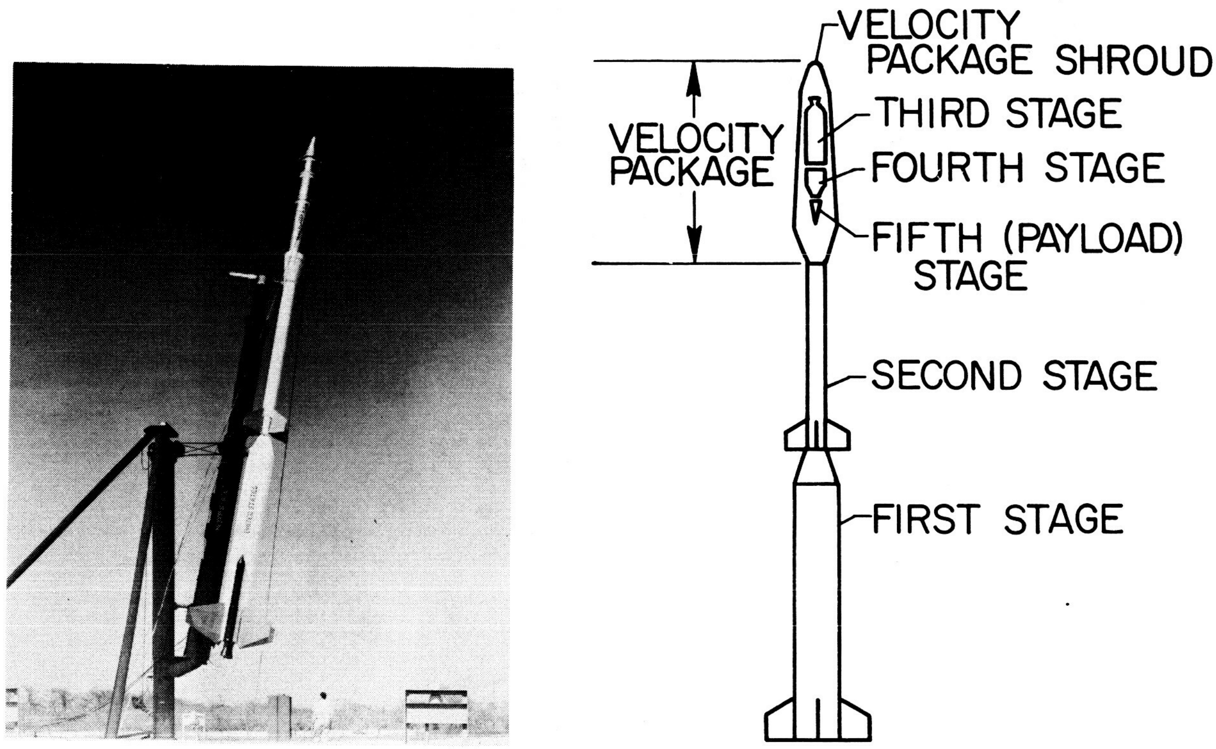

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Figure 9.- Five-stage trailblazer II reentry research vehicle.

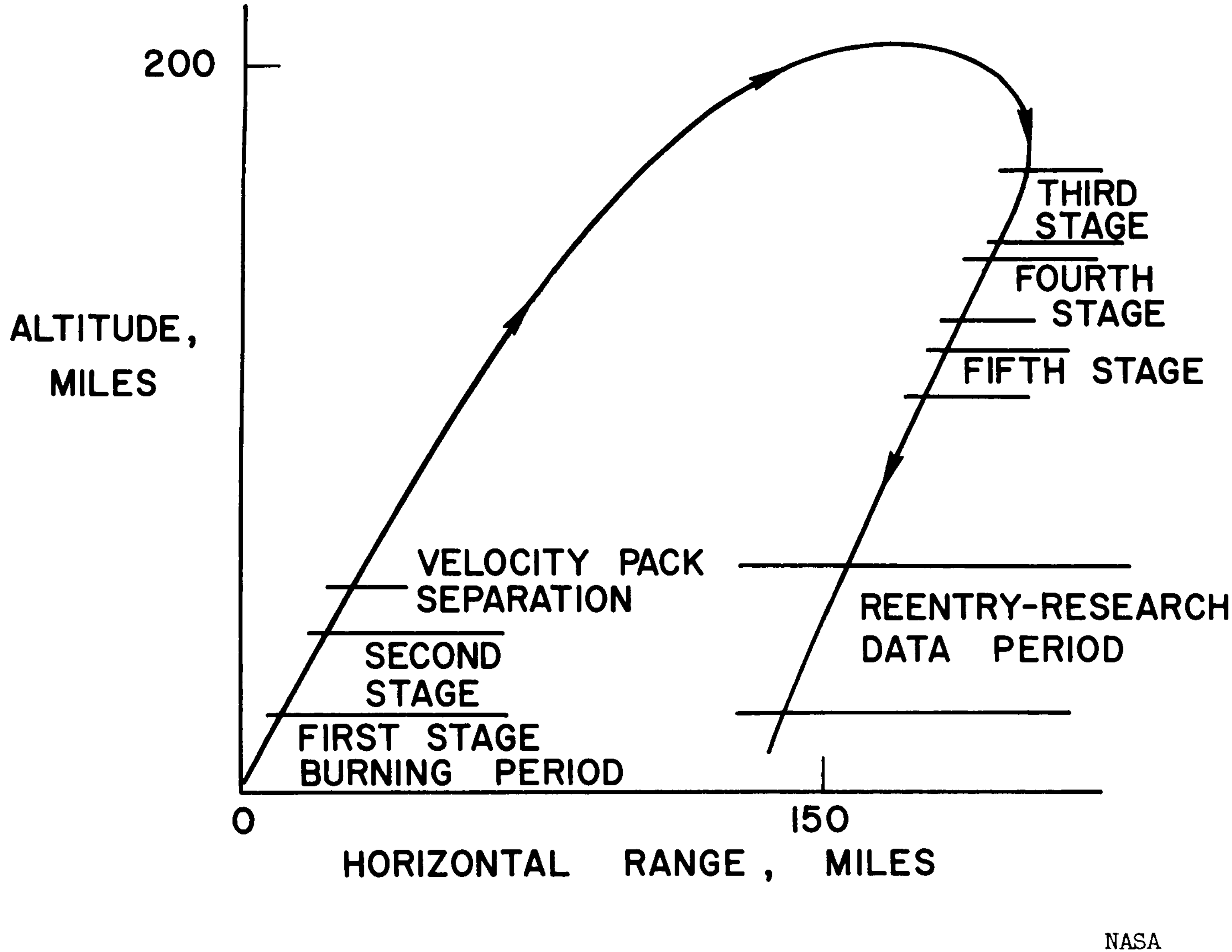

Figure 10.- Trailblazer II trajectory.

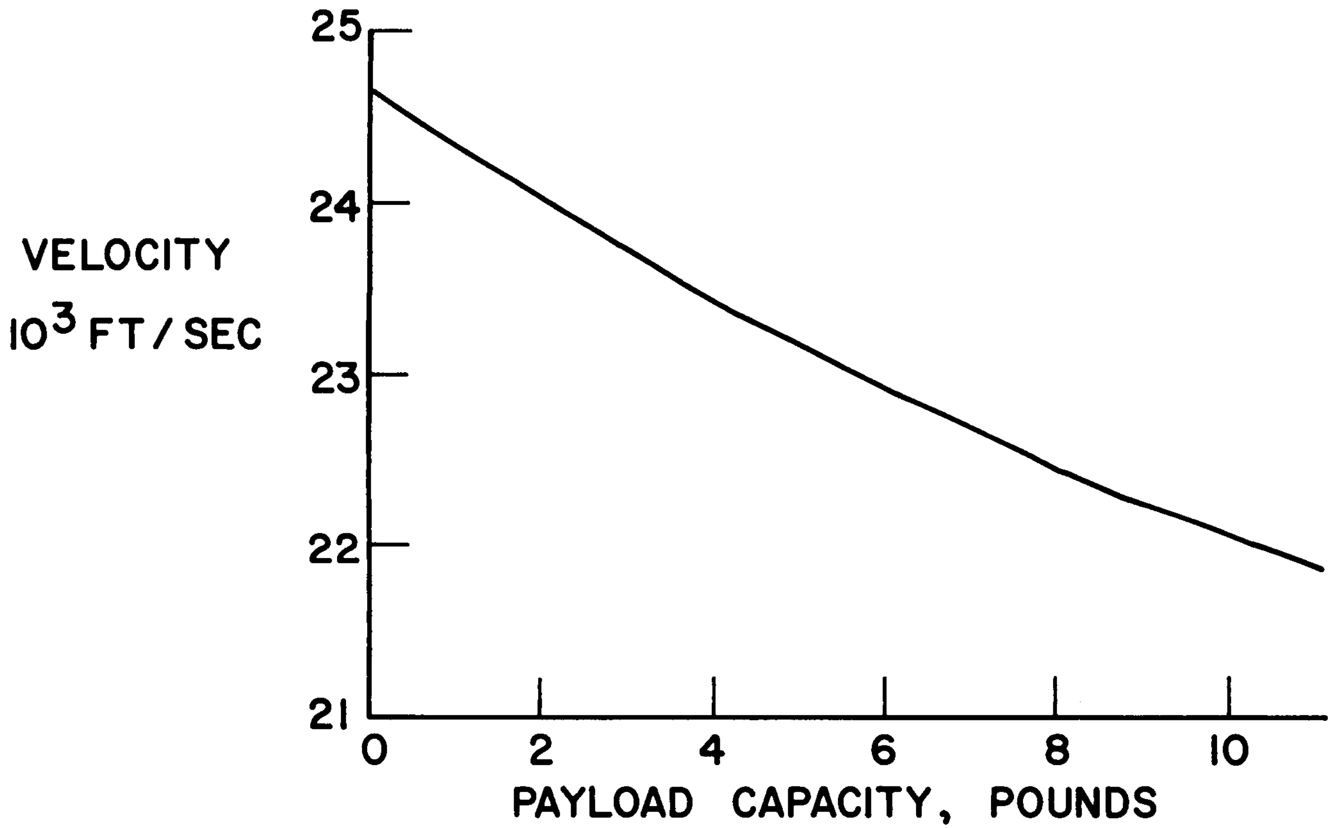

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Figure 11.- Typical trailblazer II payload velocity capability.

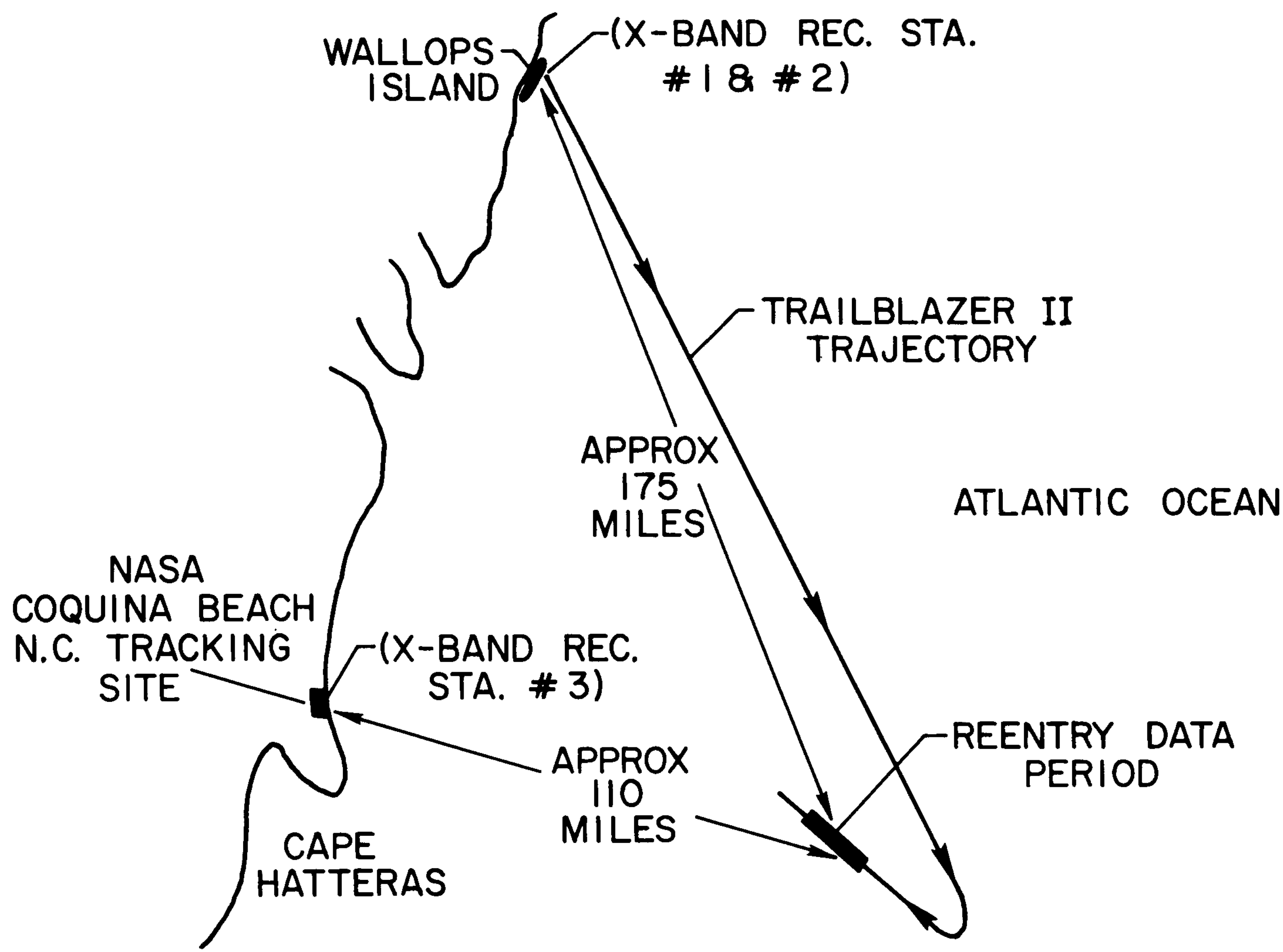

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Figure 12.- Trailblazer trajectory plan view.

NASA-Langley, 1963